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Abstract. There have been years of discussion and controversy about the existence of very thin and stable temperature sheets and their relationship to the VHF radar aspect sensitivity. It is only recently that very high-resolution in-situ temperature observations have brought credence to the reality and ubiquity of these structures in the free atmosphere and to their contribution to radar echo enhancements along the vertical. Indeed, measurements with very high-resolution sensors are still extremely rare and rather difficult to obtain outside of the planetary boundary layer. They have only been carried out up to the lower stratosphere by Service d'Aéronomie (CNRS, France) for about 10 years. The controversy also persisted due to the volume resolution of the (Mesosphere)-Stratosphere-Troposphere VHF radars which is coarse with respect to sheet thickness, although widely sufficient for meteorological or meso-scale investigations. The contribution within the range gate of many of these structures, which are advected by the wind, and decay and grow at different instants and could be distorted either by internal gravity waves or turbulence fields, could lead to radar echoes with statistical properties similar to those produced by anisotropic turbulence. Some questions thus remain regarding the manner in which temperature sheets contribute to VHF radar echoes. In particular, the zenithal and azimuthal angular dependence of the echo power may not only be produced by diffuse reflection on stable distorted or corrugated sheets, but also by extra contributions from anisotropic turbulence occurring in the stratified atmosphere. Thus, for several years, efforts have been put forth to improve the radar height resolution in order to better describe thin structures. Frequency interferometric techniques are widely used and have been recently further developed with the implementation of high-resolution data processings. We begin by reviewing briefly some characteristics of the ST radar echoes with a particular emphasis on recent works. Their possible coupling with stable sheets is then presented and their known characteristics are described with some hypotheses concerning their generation mechanisms. Finally, measurement campaigns that took recently place or will be carried out in the near future for improving our knowledge of these small-scale structures are presented briefly.

Key words. Meteorology and atmospheric dynamics (turbulence; instruments and techniques) – Radio Science (remote sensing)

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1 Introduction

The Very High Frequency (VHF) Mesosphere-Stratosphere-Troposphere (MST) radars are dedicated to studying lower and middle atmosphere physics. However, a clear interpretation of the radar observations is needed for reliable and accurate estimates of atmospheric parameters. In addition, a better understanding of the VHF radar measurement physics is fundamental for a better knowledge of the nature of the clear-air structures and their generation mechanisms. Thus, for many years, studies have been performed to unravell the backscattering mechanisms that generate the radar returns. In spite of these investigations, the signatures of the radar signals for the different processes (such as scattering from isotropic or anisotropic turbulence, partial and diffuse reflection from thin horizontally stratified and strong refractive index gradients) are still not well understood.

Accordingly, the definition of layers detected by the radars ("echoing layers") related "atmospheric layers" has not been well established yet. In the present work, we use the very broad definition introduced recently by Naström and Eaton (2001) which is based on the vertical domain of enhanced echo power and on the persistance of echoes as a signature of their horizontal extent. Such a definition can be generalized to any direction of observation, but it is worth noting that it includes features of very different scales and of entirely different origins with a wide range of physical processes. For the echoing layers, we should also note that the thickness does not necessarily represent the vertical extent

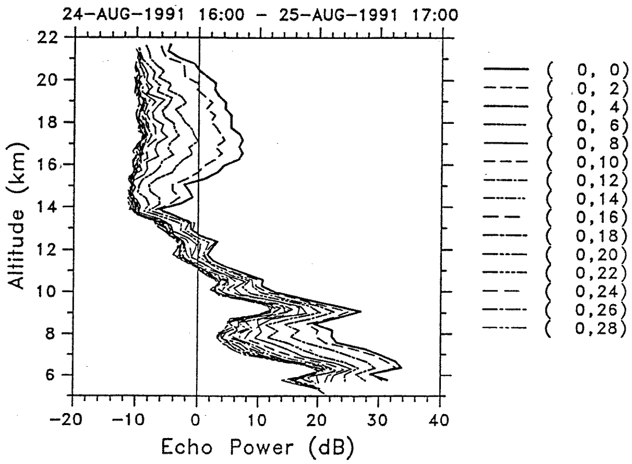

Fig. 1. Vertical power profiles averaged over 1 hour and measured by the 46.5 MHz MU radar in vertical and 15 oblique directions (after Tsuda et al. (1997a). These observations are very typical of the characteristics of aspect sensitivity observed around 50 MHz. However, for shorter time scale averaging, the profiles can exhibit thin echoing layers of vertical echo enhancement, as in Jain et al. (1997) with the Indian MST radar.

where the refractive index inhomogeneities occur, primarily because the radar is limited by its range resolution and gives a smeared representation of the real structures. On the other hand, for studies making use of in-situ observations, the vertical extent of atmospheric structures are essentially defined by the vertical gradient of the temperature (or refractive index). This gradient is very weak and very strong for a so-called "layer" and "sheet", respectively, according to the terminology used by Woods (1968, 1969), for example, in studies of oceans or lakes. In the present paper, we will also use this definition for the term "sheets" even if the term "laminae" is also sometimes used. Note that the sheets refer only to structures of vertical extent of the order of the radar wavelength and not for the widely vertically extended structures presenting a large-scale temperature gradient. The term "turbulent layer" will be used for the structures in which random temperature or humidity fluctuations are observed. "Sheets" and "turbulent layers" can be associated respectively with "reflecting layers" and "scattering layers" used in radar literature regarding the manner in which both structures may contribute to the radar echoes.

The controversy on the effective backscattering mechanisms and nature of the echoing layers remains because radar measurements alone are not sufficient to solve the problem and because there is a lack of in-depth knowledge of the morphology and properties of the air inhomogeneities at small scales (several meters or less). Few experiments have been performed to obtain direct measurements at high-spatial resolution by in-situ techniques. This is probably due to the fact that many technical problems need to be resolved for probing the free atmosphere by balloons at such a resolution and that the knowledge of the small-scale structures did not seem to be of direct importance for meteorological applications.

However, several teams specialized in atmospheric turbulence research took up the challenge and after a few years, significant progress towards the description of the atmospheric structures at a meter-scale or less have been achieved. The MST radar echo interpretation was also improved during the last decade due to the improvement of the radar processing techniques for higher range resolutions.

In this review, progress in the description and interpretation of the VHF radar echoes is first presented. Since earlier references on observations and theory can be found in previous review papers by Röttger and Larsen (1990) and Gage (1990), for example, we will primarily stress the recent investigations and discuss them in light of direct observations of atmospheric temperature (and humidity) sheets. A synthesis of the known characteristics of these stable structures is then presented, and some hypotheses proposed for explaining the generation mechanisms are discussed. Finally, we introduce experiments that took place or will be carried out in the near future for improving our knowledge of these thin atmospheric structures.

2 Aspect sensitivity of the VHF radar echoes

An essential property of the ST radar echoes operating at the lower VHF band is the dependence of the received power as a function of the zenith angle. Indeed, shortly after the development of the technique (Woodman and Guillén, 1974), it was observed that the echo power often strongly decreases as the radar beam is pointed away from the zenith. For historical reasons, this phenomenon referred to as "aspect sensitivity" even if "zenithal aspect sensitivity" would be more accurate. The azimuthal power dependence (or anisotropy) recently described in detail has been overlooked for a long time probably because it is technically difficult to investigate accurately with most of the available ST radars. Despite its weak intensity, the azimuthal dependence can reveal important characteristics of the scatterers, as discussed later.

The first (zenithal) aspect sensitivity observations in the lower atmosphere were reported by Röttger and Liu (1978) with the 53-MHz Sousy radar, and Gage and Green (1978) with the 40.5-MHz Sunset radar. Since these pioneer works, a large number of observations confirmed the phenomenon at VHF (e.g. Röttger and Larsen, 1990, and references therein; Hocking et al., 1990; Chu et al., 1990; Yoe et al., 1994; Hooper and Thomas, 1995; Jain et al., 1997, Palmer et al., 1998b, Tsuda et al., 1997a; Worthington et al., 1999a,b, 2000a). A recent example of the zenith angle dependence of the radar echo power with the Japanese Middle and Upper atmosphere (MU) radar is given in Fig. 1. Different techniques have been developed for aspect sensitivity studies, which make use of several beams (as in Fig. 1) operating sequentially or simultaneously. Radar Imaging techniques with High-Resolution data processing methods recently applied to MST radar studies can also be used for such investigations. A brief description of these techniques are is given in the Appendix.

2.1 Consequences of aspect sensitivity

2.1.1 Biases on horizontal and vertical wind velocity measurements

Aspect sensitivity may produce an underestimate of the horizontal wind measured with the Doppler Beam Swinging (DBS) method (at least 3 beams) due to an effective radar beam-pointing angle in the oblique directions closer to the zenith than to the true beam direction (see Hocking, 1997 for a detailed review of wind measurements by MST radars). However, it was experimentally found by Tsuda et al. (1986) and Luce et al. (2001d) that zenith angles larger than 10 degrees can be used to avoid or drastically reduce this effect for radar systems with narrow beams (of the order of several degrees). The aspect sensitivity can also affect the vertical velocity measurement if the aspect sensitive turbulent layers or sheets are tilted with respect to the horizontal, as discussed recently by amongst others Palmer et al. (1998b), Chau and Balsley (1998), Worthington, (1999b), and Kawano et al. (2001). This phenomenon can be produced by the tilt of isentropic surfaces since the atmospheric layers can (at least on some occasions) be parallel to the isentropes (Bertin et al., 2000), by the effects of gravity waves (e.g. Naström and VanZandt, 1996) including mountain or lee waves (Caccia et al., 1997; Worthington et al., 2000b; and a review by Röttger, 2000) or by the onset of Kelvin Helmholtz Instability (e.g. Muschinski, 1996; Worthington and Thomas, 1997).

These tilt effects can be suppressed or at least reduced by averaging over a long period (several hours), since the effective beam tends to be centered on the zenith, as shown by Worthington et al. (1999a,b, 2000a). However, if the tilts are a consequence of orographic effects, biases can occur also for long-term averages (Worthington et al., 2001).

2.1.2 Errors in isotropic turbulence parameter measurements

A VHF ST radar offers the possibility of performing experimental studies on atmospheric turbulence, for example, theoretically investigated by Booker and Gordon (1950), Ottersten (1969), or Tatarski (1971). In a stratified fluid, turbulent events are classically interpreted as the result of flow instabilities (e.g. shear instabilities, convective instabilities in the troposphere, gravity wave breakings). However, the determination by VHF radars of turbulence parameters as the refractive index structure constant C_n^2 which describes the intensity of the isotropic turbulence in the inertial sub-range or the eddy dissipation rate ϵ (e.g. recently Cohn, 1995; Hocking, 1996; Delage et al., 1997; Hocking and Wu, 1997; Hermawan and Tsuda, 1999; Nastrom and Eaton, 1997, 2001; Furumoto and Tsuda, 2001; Tozza et al., 2000) within the stratified atmosphere can be biased by the contribution of aspect sensitivity. Clear evidence of aspect sensitivity effects was shown by Röttger (1980a) and Hocking (1986) due to the presence of thin peaks clearly superimposed to a larger Gaussian distribution in the Doppler spectra. The turbulence parameters must then be obtained after carefully removing the aspect sensitive components (but this operation can be extremely fastidious) or by using a radar beam sufficiently oriented far away from the zenith with any sidelobe oriented toward the vertical. The isotropic level is thought to be detected for a zenith angle larger than ∼10–15° (e.g. Green and Gage, 1980; Röttger et al., 1981; Tsuda et al., 1986; Hocking et al., 1990). However, some recent results obtained with a Beam-Scanning analysis (see appendix) emphasized that residual aspect sensitivity can occur at larger zenith angles with an azimuthal dependence up to 20° (Tsuda et al., 1997a), or even 30° in extreme cases (Worthington et al., 1999a,b). These results seem to indicate that a very large zenith angle should be used in order to completely suppress the aspect sensitivity effects at lower VHF. In our view, further investigations should be performed with a statistical approach in order to confirm or refute the universal character of these recent observations which can be extremely useful for the interpretation of the radar echoes.

2.1.3 Stability measurements

Since the vertical echo power was found to be related to the atmospheric static stability, i.e. to the vertical gradient of potential temperature (e.g. Gage and Green, 1978; Gage et al., 1985; Tsuda et al., 1988; Chu et al., 1990; May et al., 1991), an ST radar is, therefore, a useful tool for the detection of the tropopause and fronts (e.g. recently Hooper and Thomas, 1995; Caccia and Cammas, 1998; Campistron et al., 1999; Vaughan and Worthington, 2000; Caccia et al., 2000). However, because the associated echo layers are not always aspect sensitive, the relationship between aspect sensitivity and stability is not direct. Worthington and Thomas (1997) and Worthington (1999a,b) used aspect sensitivity associated with tilted stable layers and the resulting power imbalance between oblique radar beams for deriving information about horizontal wave vectors of the mountain waves. Vaughan and Worthington (2000) reconstructed the scenario of a tropopause fold event and could detect the intrusion of the stratospheric air masses due to the stability measurements with the Aberystwyth VHF radar. Caccia et al. (2000) also reported that stability measurements by ST radars are useful for the detection of cut-off low events characterized by potential vorticity anomalies.

2.1.4 Improved sensitivity along the vertical

Aspect sensitivity also provides more reliable measurements at higher altitudes in the vertical direction than in oblique ones due to larger signal-to-noise ratios and detectability levels. Thus, wind velocity estimates in the DBS mode are limited by the detectability level of the spectra in oblique beams. With the Spaced Antenna technique, which only makes use of vertical beams, the aspect sensitivity can lead to more reliable estimates of wind velocity at higher altitudes than those obtained with the DBS technique (e.g. Hocking, 1997).

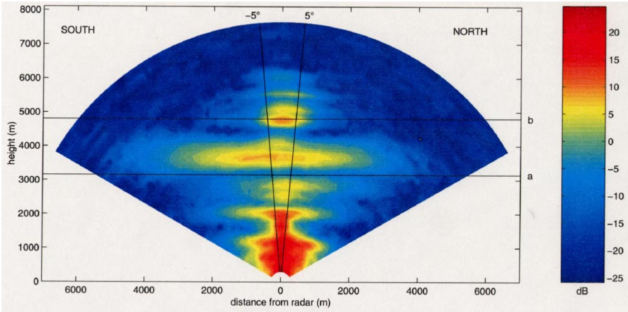

Fig. 2. 2D Map of signal-to-noise ratio obtained in a zonal plan over a 10 minute integration with the Provence radar using a Sequential Post Beam Steering (SPBS) technique. The half-power beamwidth is indicated by the radial lines at −5 and +5 degrees. The structure observed around the 4.8 km altitude clearly indicates a strong aspect sensitive echoing layer. Around 3.5 km, a less aspect sensitive echoing layer is also observed with a maximum off the zenith. The decrease in reflectivity at low elevation angles results from the loss of sensitivity of the radar (after Hélal et al., 2000).

2.2 Main characteristics of echo power

Aspect sensitivity is typically of the order of 10–20 dB compared to an oblique radar beam oriented more than 10 degrees away from the zenith. However, the phenomenon is also spatially and temporally extremely variable since it may depend on height, local geographic parameters such as orography, seasons and latitudes, or on meteorological conditions (passage of fronts, convection events, jet streams, etc.). It also depends on the radar parameters (e.g.wavelength, azimuth and zenith angle of the oblique radar beams, angular aperture of the main lobe, range resolution, etc.). It is then impossible to describe this phenomenon accurately and it is sometimes difficult to conclude if some observations are related to exceptional events or are statistically representative of the phenomenon.

2.2.1 Height dependence

Aspect sensitivity is primarily observed in the lower stratosphere and around the tropopause for radar operating approximately at 50 MHz. It is not systematic in the troposphere but it can be observed, as seen in Fig. 1 and also during tropopause fold events due to the intrusion of more stable air masses from the stratosphere or the passage of a frontal zone (see Sect. 2.1 for references). Hocking et al. (1986) performed measurements up to the 30 km altitude with the Sousy radar and observed that the phenomenon was not very pronounced in the middle stratosphere (above ≈ 18 km). However, it is often difficult to estimate correct aspect sensitivity values at higher altitudes with most of the ST radars because the atmospheric signals often disappear below the noise in oblique directions.

2.2.2 Aspect sensitivity factor

Zenithal power dependence in dB scales is sometimes more or less Gaussian-like (e.g. Gage, 1990, and references therein; and recently Jain et al., 1997; Tsuda et al., 1997a; Luce et al., 2000b) but can also reveal exponential or linear shapes and can depend on the azimuth (e.g. Worthington et al., 1999b). For describing the zenithal dependence with a single parameter, Hocking et al. (1986) modelled this dependence by using a Gaussian distribution and defined an aspect sensitivity factor (also called aspect angle) θ_s which corresponds to the e^{-1} half-width of the Gaussian angular pattern of the echo power, assuming maximum echo power from the zenith (not to be confused with the angle for which the aspect sensitivity is no longer observed). This parameter does not contain information on the echo power enhancement along the vertical. This is why bias on θ_s can be important when aspect sensitivity is not very pronounced. Estimates of θ_s recently given by Campistron et al. (1999) with the 45-MHz CRA radar, Worthington et al. (2000a) with the 46.5-MHz MU radar and Chen et al. (2000) with the 49.9-MHz Jicamarca radar are typically a few degrees (2–4 degrees) in the stable lower stratosphere. In the troposphere, the aspect angle is generally larger but can also be occasionally very small, as indirectly reported by Hélal et al. (2001) with the Sequential Post-Beam Steering technique (see Appendix) and shown in Fig. 2.

However, the aspect angle estimates can depend on the method used for the calculations. The estimates from the spectral Doppler width give larger values than those obtained from the echo power (Campistron et al., 1999) leading to ambiguity in the interpretation of the backscattering mechanisms, according to Hocking and Hamza's (1997) criterion, which will be discussed later.

2.2.3 Frequency dependence of aspect sensitivity

If aspect sensitivity is observed in the lower VHF band at least up to 72.4 MHz (Luce et al., 1995) the phenomenon was not observed at UHF frequencies, i.e. 430 MHz and higher frequencies in the lower atmosphere (Balsley and Peterson, 1981; Watkins and Wand, 1981; Sato and Woodman, 1982). An isotropic mechanism dominates at these frequencies, such as at VHF, when the beam is pointed far enough away from the zenith. However, very few data sets have been presented until now and one should not discount that aspect sensitivity may occasionally occur for specific or sporadic events. In our view, frequency dependence merits further exploration with extended data sets and multi-frequency comparisons, as performed by Röttger (1986).

2.2.4 Coherence of the aspect sensitive echoes

The aspect sensitive echoes around the vertical are generally associated with a narrower spectral width than the isotropic contribution (e.g. Tsuda et al., 1986). This observation indicates that the scatterers producing radar echoes at vertical

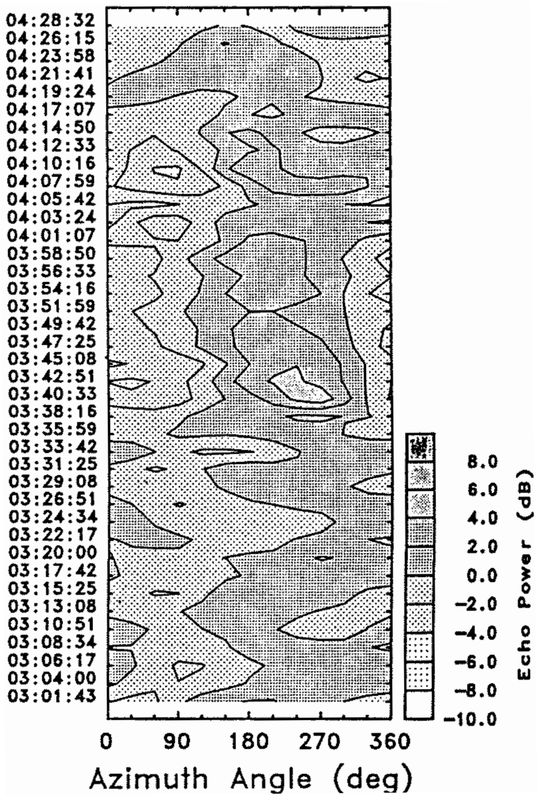

Fig. 3. Contour plot of azimuth angle variations of the echo power as a function of time (every 137 s) at 6 degrees off tbe zenith and a 6.85 km altitude with the MU radar. For this case, single humped time variations are clearly observed (after Tsuda et al., 1997b).

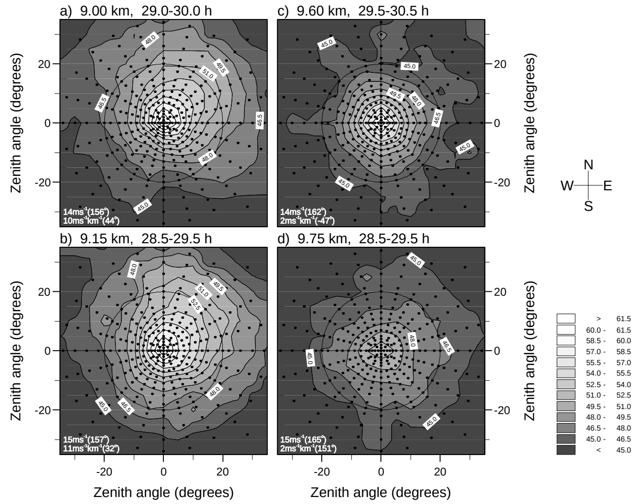

Fig. 4. Horizontal maps of echo power distribution patterns with the MU radar averaged over 1 hour with 320 directions for four tropospheric heights (9.00, 9.15, 9.60 and 9.75 km). Such studies are difficult to perform at stratospheric heights due to the loss of sensitivity of the radar when the number of beam directions is large. **(a** and **(b** show a skew of the power pattern in the direction of the wind shear (about 10 m s^{-1}km^{-1}). The maximum of echo power is observed overhead. In some azimuths, the isotropic level is not observed before 30° off the zenith (after Worthington et al., 1999a).

incidence are less time-fluctuating than the scatterers responsible for the echoes received off the zenith. An equivalent result was obtained by Röttger and Liu (1978) and Röttger (1980b) by estimating the integral-scale correlation time. The authors found that this parameter to be much longer in the vertical direction than in the oblique, even though this result was contested by Woodman and Chu (1989) because the correlation times were too long to be attributed to atmospheric events.

2.2.5 Azimuthal dependence of echo power

The azimuthal (or horizontal) power dependence strongly depends on the time resolution (e.g. recently Tsuda et al. 1997b; Palmer et al., 1998b; Worthington et al., 1999a,b, 2000a). Strong variations are generally observed on short time scales (several minutes or less) but the phenomenon can persist even after averaging over several hour intervals. Figure 3 indicates azimuth angle variations of the echo power as a function of time at 6 degrees off the zenith with the MU radar. The profiles can present single humped time variations, as indicated in Fig. 2 or double time variations, as shown in Fig. 4 (the second case seems to be more exceptional.) The ratio of the maximum to the minimum echo power was typically 5 dB but could exceed 15 dB for some cases. Recently, Worthington et al. (1999a,b, 2000a) presented horizontal distribution patterns of echo power at tropospheric heights using the Beam-Scanning technique with 320 directions. With the MU radar, echo power maps sometimes exhibit strong azimuthal variations even after averaging over 1-hour intervals between -30 and 30 degrees off the zenith with a skew of the echo power distribution (Fig. 4). Even at 30° off the zenith, the ratio of the maximum to the minimum 1-hour averaged echo power can be of the order of 4 dB. It is worth noting that horizontal anisotropy was also observed by Van Baelen et al. (1991) by using Post Beam Steering (their Fig. 10, for example), and by Palmer et al. (1998a) (their Fig. 6, for example) with a Radar Imaging technique within the radar lobe.

Horizontal distribution patterns of echo power close to the zenith in the troposphere also exhibit fast variations over time scales of a few minutes and over adjacent radar gates as reported by Tsuda et al (1997a), Worthington et al. (2000a), and also by Chau and Woodman (2001) using High-Resolution radar Imaging techniques. Since the atmospheric structures are more stable within the lower stratosphere, the results can significantly differ for stratospheric echoes. However, at present, the loss of sensitivity of the radars inherent to the simultaneous use of many beams makes it difficult to conduct such experiments in the lower stratosphere, especially if the tropopause is high.

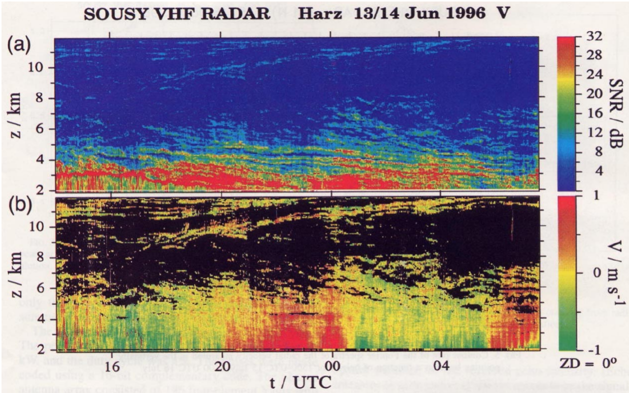

Fig. 5. (Top) Time-height cross sections of vertical SNR measured with the 53.5 MHz Sousy radar at a 0.5 μs pulse duration (75-m range resolution) and time resolution of 33 s and (bottom) the corresponding radial velocities measured with the vertically pointing beam. The most striking feature is the large number of thin and long-lived echoing layers. Some of them can be thinner than the 75-m range resolution used (after Rüster et al., 1998).

2.2.6 Aspect sensitivity associated with maximum echo power off zenith

As already discussed in Sect. 2.1, aspect sensitivity can be associated with a maximum power off the zenith. This phenomenon could result from atmospheric targets located away from the zenith, as already observed at mesospheric heights by Röttger and Ierkic (1985), but more likely from tilted turbulent layers or tilted sheets in the lower atmosphere. The tilt measured with respect to the horizontal can generally be of the order of a few degrees or less, on average, (e.g. Röttger and Larsen, 1990, and references therein; Larsen and Röttger, 1991; Larsen et al., 1991; Palmer et al., 1991, 1993, 1998a,b; Chau and Balsley, 1998; Worthington et al., 1999a,b, 2000a; Kawano et al., 2001; Hobbs et al., 2000) or much more, such as 10 degrees in extreme cases, as reported by Worthington and Thomas (1997). Worthington et al. (1999a,b) also found that the zenith angle where the maximum echo power was observed is more pronounced in the troposphere than in the stratosphere.

Some studies showed that the tilt of the aspect sensitive echoing layers are related to instabilities. Worthington and Thomas (1997) reported that power imbalances between symmetric beams (resulting from a tilted echoing layer) were associated with a strong wind shear caused by long-period gravity waves. This result was confirmed by Worthington et al. (1999a,b) due to the measurements of horizontal maps of aspect sensitivity as discussed above. They also found that the wind shear direction corresponded very well with the skew of the power distribution.

Recent studies with High-Resolution Imaging techniques tend to show that the model of a tilted turbulent layer or tilted sheet could be an oversimplification of the real atmospheric structures that contribute to the radar echoes. Chau and Woodman (2001) showed several examples where at least 2 maxima were detected within the main lobe after Capon's or Maximum Entropy data processings (see Appendix), indicating the presence of at least 2 sources of backscattering. From our point of view, this result seems to imply that an apparent tilt could also result from the contribution of several facets of a distorted sheet surface or from the contribution of isolated scattering volumes within the radar beam.

3 Characteristics of the echoing layers seen by ST radars

3.1 Observations of echoing layers in standard mode

The standard mode corresponds to the DBS observational mode described in the Appendix. Many radar observations in this configuration have revealed the presence of thin echoing layers, as most recently observed by Röttger (2001) in the polar atmosphere with the SOUSY Svalbard Radar (SSR). Those detected overhead are primarily observed in the stable atmosphere, i.e. just above the tropopause and in the lower stratosphere. Apparent layered structures can also be found within the troposphere even if it is less stratified than the stratosphere, but these can be destroyed by strong convective events (e.g. Wakasugi et al., 1985; Rüster et al., 1998). They can thus appear less persistent than the echoing layers in the lower stratosphere. This persistence (which can be related to a horizontal extent if they are advected by the wind) is extremely variable (from several minutes or less, to several tens of hours). The shortest ones could be related to punctual and local atmospheric events, and therefore, are very difficult to analyze in detail.

Generally, the well-defined echoing layers observed with ST VHF radars are associated with aspect sensitivity (e.g. Wakasugi et al., 1985; Tsuda et al., 1986, 1988; Kilburn et al., 1995; Jain et al. 1997). Recently, Rüster et al. (1998) made use of a 0.5-μs duration pulse (75-m range resolution) with the Sousy radar and revealed isolated echoing layers of a thickness less than 75 m (Fig. 5). Thus, it is often concluded that the atmospheric structures that produce the echoing layers are confined within volumes of vertical extent much smaller than the range resolution used (e.g. Röttger and Schmidt, 1979; Hocking and Röttger, 1983; Sato et al., 1985) and the Frequency Domain Interferometry techniques applied to MST radars (see below) seems to confirm this assertion. The separation in height of the echoing layers can be several hundred meters or a few kilometers (e.g. Röttger, 1980b; Tsuda et al., 1988; Jain et al., 1998) but this result can be a direct consequence of the vertical resolution used and statistical studies on the topic have not been presented until now.

A better range resolution, i.e. up to 15 m, can be achieved by UHF radars. They could observe echoing layers thinner than 60 m, as reported by Ierkic et al. (1990), Wand et al. (1983), Delage et al. (1997) and Bertin et al. (2000), for example. With FMCW radars at several GHz, echoing layers of only several meters in thickness are very often observed (see Gossard, 1990, for a review on the topic and references on observations with FMCW radars and recently Eaton et al., 1995). Thin echoing layers can also be detected within the boundary layer by using acoustic radars (e.g. Schubert, 1977). At least in the free atmosphere, UHF radar echoes seem to be unambiguously produced by isotropic turbulence (at the scales corresponding to the Bragg scale, i.e. several cm, the stability effects should be of minor importance), as stressed by Röttger and Larsen (1990) and references therein.

3.2 Observations at VHF with other modes

The classical technique consisting of transmitting a single (optionally phase-coded) pulse is not sufficient for an unambiguous estimate of the vertical extent of atmospheric structures that contribute to the ST radar echoes, since some echoing layers appear thinner regardless of the range resolution used. The improvement of the range resolution of the VHF ST radars implies a widening of the receiver bandwidth, which actually causes technical problems and could be infeasible in some cases due to frequency band allocation regulations. More sophisticated methods are thus needed for improving the resolving power of the ST radars.

3.2.1 Observations with oversampling

Measurements with oversampling introduced by Röttger and Schmidt (1979) could be useful for the identification of isolated and very thin atmospheric structures with respect to the range resolution used. As shown by the authors, the technique was successful for the detection of cats-eye structures.

In the case of an "infinitely thin layered structure", the vertical power profile corresponds to the squared radar range weighting function. Fukao et al. (1988) presented a case where the echo power profile closely resembled this function for measurements at 10 degrees off the zenith, indicating the presence of a very thin atmospheric structure compared to the 150-m range resolution used. This structure caused an apparent wind shear. However, this technique has not been sufficiently used in spite of its potential and only a very few number of observations have been performed for vertical echo studies.

3.2.2 Observations with dual Frequency Domain Interferometry technique

The dual Frequency Domain Interferometry (FDI) technique was introduced by Kudeki and Stitt (1987) in MST radar studies within the mesosphere. This technique consists of estimating the coherence of the signals received at two closely spaced transmitter frequencies. It permitsthe improvement of the range resolution if a single scattering target contributes to the radar echoes within the range gate. Indeed, it can be shown that in this case, the signal coherence is related to its thickness, and the phase is related to its position.

In the lower atmosphere, the applications of the FDI technique, using an initial 300-m range resolution, indicated the presence of 50–150 meter thick echoing layers within the lower atmosphere (e.g. Palmer et al., 1990b; Liu and Pan, 1993; Kilburn et al., 1995). An example of the height-time cross section of the vertical signal-to-noise ratio after dual FDI processing with the MU radar is given in Fig. 6. However, the FDI results can be difficult to interpret for many reasons. First, above several tens of kilometers in altitude, the simultaneous effects of the spherical curvature of the wavefront and the unknown horizontal correlation length of the irregularities become important. Thus, as stressed by Luce et al. (1999), the problem can no longer be resolved by a closed set of equations and the solution obtained by ignoring these combined effects can be a very crude representation of the real atmospheric structures. Others limitations and strengths of the technique have also recently been studied by Luce et al. (2000a,b, 2001a) and Chen and Chu (2001). Chilson et al. (1997) and Muschinski et al. (1999) used FDI for the detection of vertical motions deduced from the variations in time of the position of the echoing layer. However, Chen and Chu (2001) stressed, in particular, that the variations of the echoing layer position deduced by FDI is not necessarily related to a real displacement of a single atmospheric structure, but can be related to the fact that more complex structures than a single Gaussian-distributed layer may generate the radar echoes (as multiple turbulent layers or sheets). Röttger et al. (2000a) also stressed that the thickness of the echoing layers deduced from FDI may not be consistent with the thickness of turbulent layers or sheets due to the study of the variations in the mean scattering center positions (at a ~ 0.1-s time resolution) using a combined Spatial and Frequency Domain Interferometry (SDI/FDI) technique (Röttger et al., 2000b). Indeed, the layer thickness deduced from coherence estimates of the echo results from a power-weighted average of the individual mean positions associated

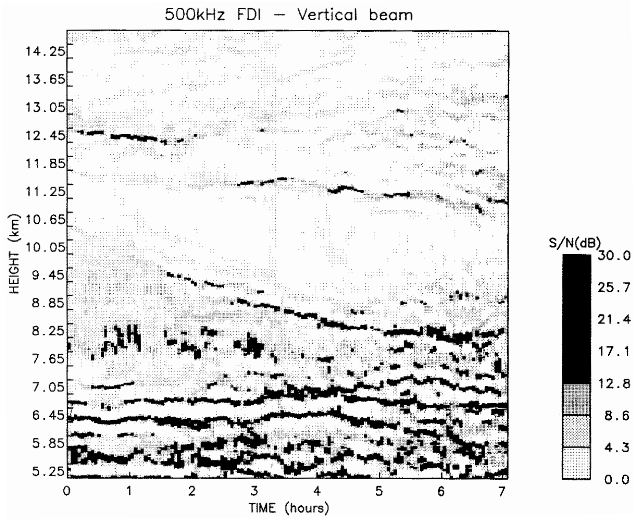

Fig. 6. Time-height cross sections of vertical signal-to-noise ratio after dual FDI processing with $\Delta f = 0.5$ MHz and an initial 300-m range resolution with the MU radar. Thinner echoing layers than 300 m can be detected and more details on their vertical displacements seem to appear (after Kilburn et al., 1995).

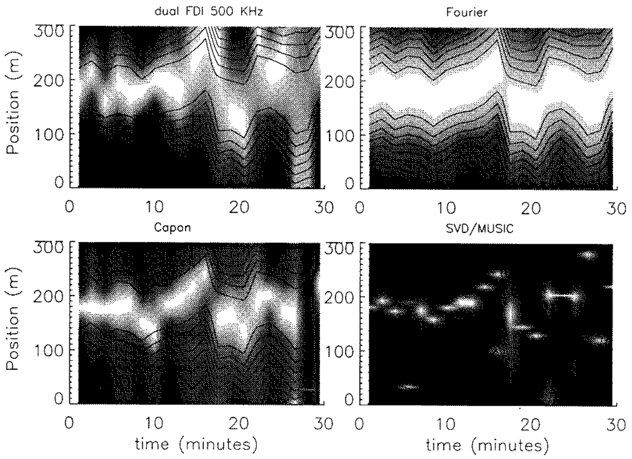

Fig. 7. Time variations of brightness distribution within a 300-m range gate estimated from a multi-FDI technique (4 frequencies between 46.25 and 46.75 MHz) with the MU radar and using (top right) Fourier Based imaging, (bottom left) Capon's method and (bottom right) MUSIC's algorithm. The result obtained with the classical dual FDI technique is given in top left. Similar features are obtained with the four data processings, but Capon's method indicates thinner structures than the dual FDI technique as also noticed Palmer et al. (2000). The MUSIC algorithm also indicates similar positions but the brightness distribution given by MUSIC is not representative of the depth of the atmospheric layer (after Luce et al., 2000a).

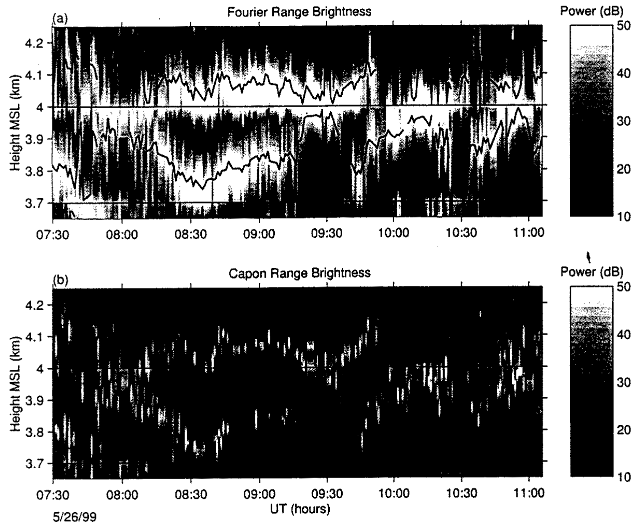

Fig. 8. Time variations of brightness distribution within two successive 300-m range gates estimated from a multi-FDI technique with the Sousy radar, (four frequencies between 53.25 and 53.75 MHz) during the SOMARE99 campaign and using (top) Fourier Based imaging and (bottom) Capon's method. The position given by dual FDI is shown by the black line. Thin echoing layers and their vertical displacements are clearly described with Capon's method. However, as in Luce et al. (2000a), the HR techniques did not reveal more complex structures than a single echoing layer in spite of their potentialities to distinguish several structures (after Palmer et al., 2000.)

with each sample of the time series and these mean positions often show deterministic variations with time. Thus, these results merit further investigations for a deeper knowledge of these mechanisms at short-time scales.

3.2.3 Observations with multi-Frequency Domain Interferometry technique

Recent developments have extended the dual FDI technique to multiple frequencies. This technique can be considered as an extension of the frequency hopping technique applied by Franke (1990) for MST radar applications. It consists of transmitting N closely spaced frequencies within N consecutive pulses for (frequency) pulse compression. It can be shown that this approach is equivalent to the Fourier Based Imaging, as discussed by Palmer et al. (1999) and Luce et al. (2001c). Since the resolving power of this method is not sufficient, some methods with constrained optimization have also been applied, such as the adaptative Capon's method (Palmer et al., 1999, 2001; Chilson et al., 2001; Yu et al., 2000; Luce et al., 2001b,c) and the MUSIC algorithm based on a singular value decomposition of the coherence matrix (Luce et al., 2001c). The High-Resolution methods seem to confirm the results given by dual FDI, i.e. a single echoing layer within the range gate (Figs. 7 and 8), and Luce et al. (2001b) presented a case where possible Kelvin-Helmholtz Instability structures (several structures within the range gate) could be detected.

These recent results with High-Resolution methods are very promising for a deep analysis of the fine-scale structures within the atmospheric temperature field. They have already confirmed, especially due to the SOusy Multi-frequency Atmospheric Radar Experiment (SOMARE) campaign (Chilson et al., 2001), that the layered atmospheric structures are much thinner than the initial 300-m range resolution used and sometimes even thinner than the 50–150 m thickness obtained by dual FDI.

4 Various interpretations of aspect sensitive echoing layers

The primary mechanism proposed for explaining the clear-air echoes was the scattering from atmospheric turbulence, which was extensively studied for the tropospheric radio wave propagation beyond the horizon (e.g. Booker and Gordon, 1950; Batchelor, 1955; Ottersten, 1969; Tatarskii, 1971). The isotropic scattering from refractive index irregularities is usually advocated for explaining the echoes at UHF (because aspect sensitivity is not observed) and at VHF, for echoes received far from the zenith (e.g. Van Zandt et al, 1978; Vernin et al., 1990; Luce et al., 1996, 1997). However, the aspect sensitivity at VHF clearly indicates that atmospheric structures with larger correlation length in the horizontal plane than in the vertical contribute to the echoes around the zenith. Views differ on the nature of the anisotropic structures and on the backscattering mechanisms. A composite model for

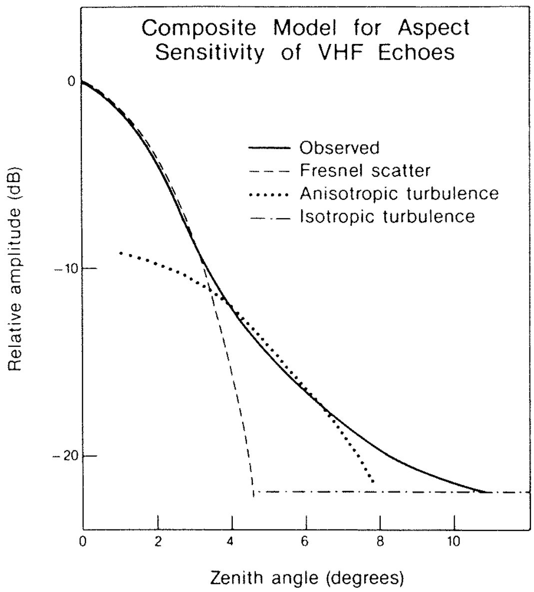

Fig. 9. Composite model for aspect sensitivity from Tsuda et al. (1986). Tsuda et al. (1997a) added the diffuse reflection on a rough surface that could replace the anisotropic turbulence in dotted lines.

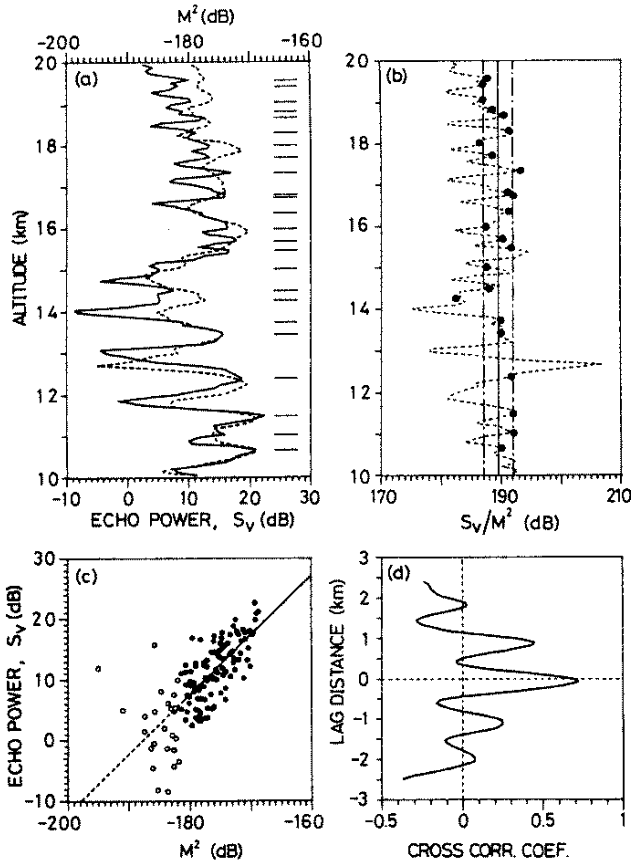

Fig. 10. (a) Comparison between a profile of the square of the vertical gradient of potential refractive index M^2 deduced from balloon measurements at a 150-m range resolution (dashed line) with a vertical echo power profile (solid line) observed by the MU radar **(b)** ratio **(c)** a linear regression curve and **(d)** cross-correlation function (after Tsuda et al., 1988). The proportionality between the vertical echo power and M^2 (and, in particular, with N^4 for dry atmosphere) seems to be systematic, indicating the VHF ST radars can provide reliable stability measurements.

interpreting aspect sensitivity has been proposed by Tsuda et al. (1986) (Fig. 9). The basic equations associated with each backscattering mechanism have been summarized, for example, by Röttger and Larsen (1990).

On the one hand, scattering solely from anisotropic turbulence (e.g. references in Röttger and Larsen, 1990; and recently, Hocking and Hamza, 1997) is often proposed for explaining aspect sensitivity. The turbulent eddies would become anisotropic due to the effects of the static stability, which is important at scales larger than the buoyancy scale L_B (e.g. Shur, 1962; Lumley, 1964; Weinstock, 1978; Hocking, 1985). Many models of anisotropic scattering mechanism were developed for different purposes by authors summarized by Gage (1990), for example, and more recently by Gurvich and Kon (1993), Doviak et al., (1996), Gurvich (1997), Holloway et al. (1997), and Chau and Balsley (1998), for example. On the other hand, partial reflection from stratified stable layers was also proposed (Röttger and Liu, 1978; Gage and Green, 1978; Röttger, 1980b). This mechanism was also speculated by Friend (1949), Friis et al. (1957), Misme et al. (1958) and Saxton et al. (1964), for example, to explain radio wave propagation beyond the horizon. The theory shows that this mechanism occurs especially at low radar frequencies, primarily depending on the thickness and shape of the layer, as stressed by Woodman and Chu (1989). To be a dominant mechanism at UHF, layers of thickness less than several tens of centimeters would have to exist. Strictly speaking, partial (or Fresnel) reflection occurs when a single or a few independent flat layers with a large horizontal extent with respect to the first Fresnel zone is embedded within the radar range gate. This condition is probably not satisfied for high altitude UHF observations. A more realistic model of diffuse (or quasi-specular) reflection (Ratcliffe, 1956) has been proposed by Röttger (1980a) for MST radar studies, taking into account the surface roughness produced by turbulence or distorted by buoyancy wave activities. Another extension of the partial reflection is the Fresnel scattering proposed by Gage et al. (1981, 1985). This mechanism involves a statistical approach since it assumes that many thin turbulent layers or sheets, highly coherent along the horizontal, are randomly distributed within the range gate. It was shown that this model provides an expression of the received power proportional to the mean squared gradient of the potential refractive index M^2, which is a measure of the atmospheric stability (Hocking and Röttger, 1983; Gage et al., 1985) or N^4 if humidity effects are negligible (Green and Gage, 1980). Experimental studies confirmed the clear relationship between M^2 deduced from in-situ measurements with the echo power received at vertical incidence (e.g. Gage et al., 1985; Tsuda

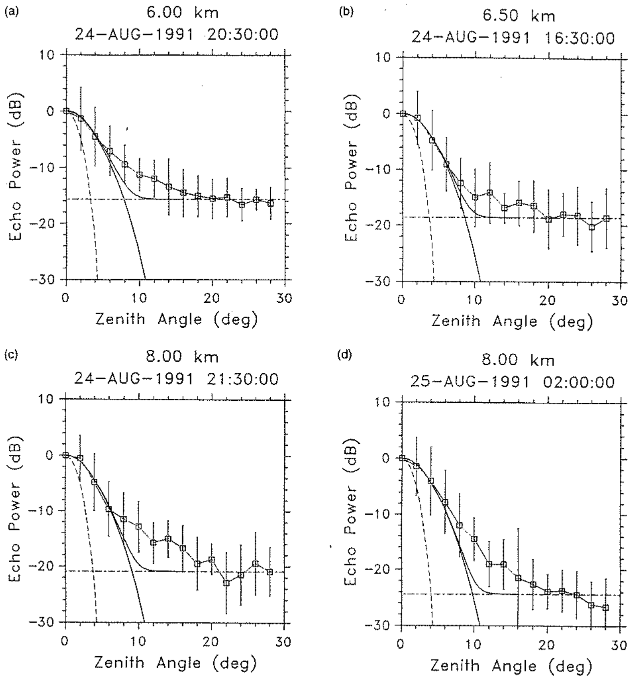

Fig. 11. Four comparisons between aspect sensitivity observations with the MU radar (squares with vertical bars indicating the standard deviation of the variations during the averaging time) with the results $Z(\theta)$ of a model based on the hypothesis of layers with a surface corrugated by gravity waves (solid lines). The dashed and dot-dash lines indicate the squared MU radar antenna gain and the turbulent scattering level S, respectively. The values $Z(\theta) + S$ are also given in solid lines. For more details, see discussions in Sect. 6 (after Tsuda et al., 1997a).

et al., 1988; Chu et al., 1990; May et al., 1991). An example is given in Fig. 10 from comparisons between MU radar and balloon measurements. This property permitted stability measurements by radars such as those discusssed in Sect. 2.1.

In combination with the isotropic model for power measurements far from the zenith, models based on anisotropic scattering mechanisms reproduce well the zenith angle dependence of the received power (e.g. Doviak and Zrnic', 1984, Waterman et al., 1985; Tsuda et al., 1986; Gurvich and Kon, 1993; Luce et al., 2000b). One of the reasons for these successful results may be the large number of "free" and sometimes unknown parameters, depending on the model, such as the vertical and horizontal correlation lengths of the irregularities that should also depend on scales. Moreover, the comparisons are usually in relative power levels leading to a simplification of the problem. Sheen et al. (1985) and Kuo et al. (1987) studied statistical distributions of radar echo power. The studies performed with the signals received along the zenith showed distributions fully compatible with volume turbulent scattering. Nevertheless, Gage et al. (1981) argued that the high static stability of the lower stratosphere is not favourable for scattering from turbulence structures. Recently, Jain et al. (1998) and Kawano et al. (2001) observed strongly aspect sensitive layers associated with high Richardson numbers indicating that the backscattering mechanism by anisotropic turbulence is not relevant for the cases presented by the authors. Röttger (1980a) argued that the large-scale correlation time of the vertical echoes is too important to be attributed to turbulent echoes. These observations are more compatible with the hypothesis of partial reflection from sheets, although Woodman and Chu (1989) argued that this mechanism was not "plausible". Indeed, very thin structures (of the order of several meters) are needed and their lifetime may not be very long due to the effect of turbulence diffusion. Moreover, the partial reflection mechanism cannot explain the slow decrease in power with the zenith angle except if diffuse reflection from rough surfaces occurs since it can reduce the specular nature of the partial reflection. Recently, Tsuda et al. (1997a, b) explained the zenithal and azimuthal variations of echo power with the MU radar from a realistic model of gravity waves corrugating a reflecting layer (Fig. 11). This model explained observations leading to a decisive interpretation of the aspect sensitivity (see Sect. 6)

It was stressed by many authors that diffuse reflection or scattering by anisotropic turbulence is very difficult to differentiate since the roughness of the layer surface and the refractive index fluctuations within the turbulent layer may be described by similar statistics. One can speculate that the conclusions obtained by Sheen et al. (1985) or Kuo et al. (1987) mentioned above result from this property.

Hocking and Hamza (1997) proposed a quantitative relation between the degree of anisotropy of turbulence and the prevailing atmospheric conditions. The authors obtained a simple criterion for differentiating the scattering from anisotropic turbulence and partial reflection from the sheets. According to their theory, if the aspect sensitivity factor θ_s is smaller than 5 degrees, the radar backscattering results from partial reflection and not from anisotropic turbulence, indicating that the recent estimates of 2–4° summarized in Sect. 2.2 are compatible with partial reflection.

Another decisive result has been previously obtained by Dalaudier et al. (1994) and Luce et al. (1995) with the observation for the first time of stable temperature sheets in the free atmosphere. A description of these structures (which have often been speculated about, but never observed before the use of high-resolution temperature sensors) is given in the following section. Dalaudier et al. (1994) and Luce et al. (1995) quantified the contribution of these thin structures to a vertical echo power of 2 VHF ST radars at 45 MHz and 72.125 MHz, and compared the observed vertical power profiles and the reconstructed profile in absolute levels. They confirmed that the partial reflection process may be dominant at least in the lower stratosphere and just above the tropopause. Moreover, it was shown by Luce et al. (1997) that the scattering from isotropic turbulence constitutes a good approximation of the radar echoes at 15 degrees off the zenith by using estimations of C_T^2 from temperature measurements with two high-resolution sensors, separated by 1 meter along the horizontal. Figure 12 shows a comparison between the ratio of the vertical echo power and

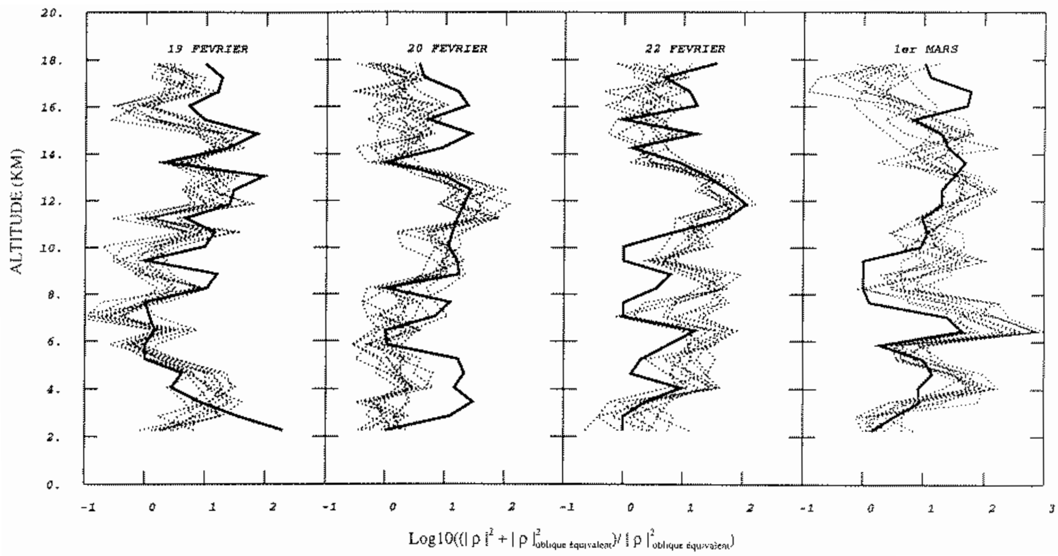

Fig. 12. (Dotted lines) Vertical profiles of the ratio of echo power measured in vertical incidence and at 15° off the zenith with the 45-MHz Provence radar during the RASCIBA90 campaign and for four periods where high-resolution balloon measurements could be performed. All the radar profiles (600-m range resolution) during the balloon ascent are indicated. (Thick solid lines) Vertical profiles of the ratio of reconstructed echo power profiles in vertical and oblique incidences from temperature and humidity measurements. The reconstructed profiles are based on the partial reflection mechanism in the vertical incidence from the temperature sheets (Luce et al., 1995) and on isotropic scattering from turbulence (Luce et al., 1997) in oblique and vertical incidences. Schematically, the profiles of ratio ([partial reflection]+[isotropic scattering])/[isotropic scattering] are calculated and compared to the radar profiles. These results clearly indicate the contribution of temperature sheets to aspect sensitivity.

the oblique one given by the models and by the radar observations. The reconstructed profile in vertical incidence is based on the added contribution of partial reflection from temperature sheets (Luce et al., 1995) and isotropic scattering by isotropic turbulence (Luce et al., 1997). The two kinds of profiles agree quite well indicating the significant contribution of the temperature sheets to the vertical echo enhancement. However, the Luce et al.'s studies did not discuss the origin of the possible horizontal anisotropy recently described in detail by Tsuda et al. (1997b) and Worthington et al. (1999a, b), for example, and did not explain the aspect sensitivity at intermediate angles between the zenith and off-vertical directions. These encouraging results for the knowledge of radar atmospheric physics also confirm that complementary observations by a ultra-high resolution in-situ technique could shed more light on the backscattering mechanisms at VHF.

5 in-situ observations of stable sheets

5.1 Observations in the free atmosphere

As indicated in the previous subsection, high-resolution temperature measurements collected during the RASCIBA90 campaign in France (Radar-Scidar-Balloons, 1990) revealed the existence of thin stable gradients (signature of sheets) in the free atmosphere coexisting with random temperature fluctuations (signature of turbulent layers) at small ($\sim$ 1 m) energetic scales (Dalaudier et al., 1994). Examples are given in Fig. 13.

The sheet structure is commonly observed in the boundary layer (Misme et al., 1958; Saxton et al., 1964; du Castel et al., 1966; Lane, 1968; Gossard et al., 1985) and in oceans (e.g. Woods, 1968; Dugan, 1984) and lakes (e.g. Thorpe, 1977; Imberger and Ivey, 1991).

Dalaudier et al. (1994) found that the sheet thickness ranges between 1 and 60 m, their temperature increase ranges between 0.1 and 3 K, and their corresponding gradient ranges between 20 and 200 K per km with some maxima of 300 K per km. It must be pointed out that they do not constitute a distinct population in the histogram of the vertical gradients, giving rise to some subjectivity in their selection. Indeed, they were selected by using a criterion of local static stability, as explained by the authors and Luce et al. (1995). Some of them (30%) show ongoing or recent mixing despite the strong static stability. This implies that the categories of "sheets" and "turbulent layers" are probably not sufficient for describing the volume in which the small-scale atmospheric structures occur. It also indicates that a more or less intimate connection could exist between both structures, as suggested by some generation mechanisms discussed in Sect. 7.

The sheets are often in groups associated with or taking part in regions of high static stability. Most of them are observed in the lower stratosphere (Fig. 14). The horizontal extent of the temperature sheets also seems to depend on their temperature increase: the stronger ΔT is, the larger the horizontal extent is, as deduced from comparisons of the high-

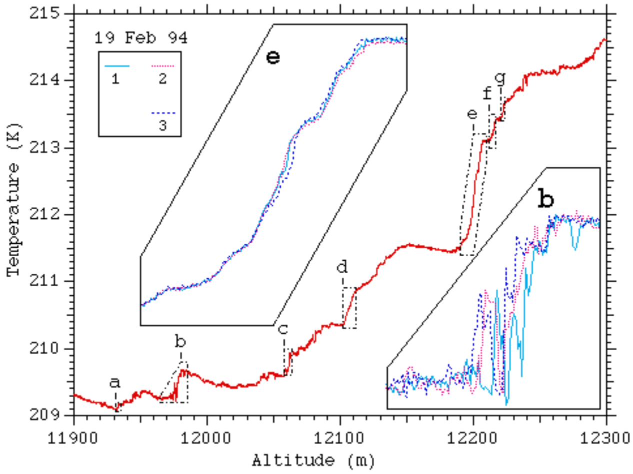

Fig. 13. Examples of temperature profiles obtained at a 20-cm vertical resolution during the RASCIBA90 campaign (France) (after Dalaudier et al., 1994). The selected sheets are encircled by broken lines. Two close-ups of sheets "b" and "e" are displayed with the three profiles measured by three sensors separated by 1 m at the top of a square. Some of the sheets present ongoing mixing as in sheet b.

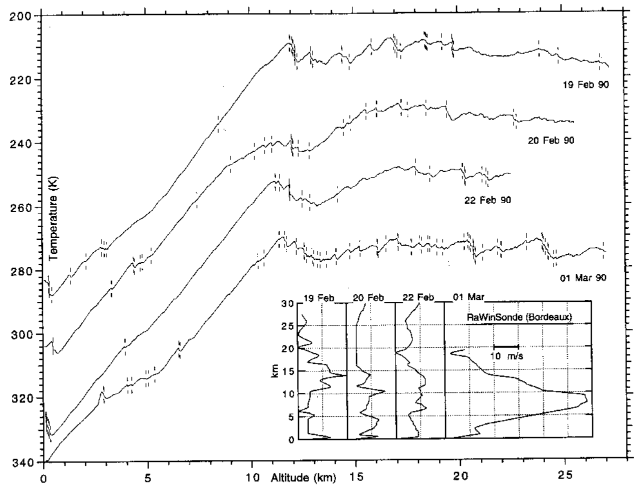

Fig. 14. The four high-resolution temperature profiles measured during the four balloon ascents during the RASCIBA90 campaign (France) and the position of the selected temperature sheets (after Dalaudier et al., 1994). The successive profiles are offset by steps of 20 K. The sheets primarily occur in a group in the region of high static stability. The sheet groups are typically separated by $\sim$ 1 km especially in the profile of 19 February 1990 which is in agreement with the typical separation of the echoing layers seen by high-resolution ST radars (e.g. Tsuda et al., 1988).

resolution profiles with those obtained with a coarse temperature sensor. These structures can present either very sharp boundaries, as shown by Luce et al. (1995) in their Fig. 2 or smoother boundaries. We can also suggest that it probably depends on the age of the sheet, as shown by Coulman et al. (1995) for larger-scale structures, and on the generation mechanism.

The probability of sheets seems to depend on the meteorological conditions, and is large near strong jet streams. They occupy a small fraction of the profiles but contribute to a large fraction of the temperature increase. The morphology of the sheets in the boundary layer is the same as in the stratosphere. In few cases, strong temperature fluctuations are observed (maybe by coincidence) below and/or above the temperature sheets. They seem to move and be distorted by the surrounding medium; local slopes seem to reach several tens of degrees. However, these preliminary estimates must be carefully considered since the sensor configuration used (4 sensors 1-m apart at the corners of a squared structure) is not really suitable for such studies.

5.2 Observations in the lower troposphere, planetary boundary layer and oceans

Kropfly (1971) reported temperature sheets as thin as 20 meters or less (some of the observed structures seem to constitute groups of thinner sheets) around the 2.9 km altitude, which is sometimes associated with very strong wind shear at the same vertical scales and without turbulence above. More recently, Muschinski and Wode (1998) also confirmed the existence of temperature sheets and observed structures as thin as several decimeters within the lower troposphere (below 800 m) due to ultra high-resolution measurements by helicopter (Fig. 15). They reported gradients of about 20–25 K/km within structures as thin as 30–40 cm. These gradients are sometimes associated with strong negative or positive humidity gradients and they are also sometimes related to a wind shear at the same scales as indicated in their Fig. 7. These results are similar to those presented by Gossard et al. (1985) in the stable stratified boundary layer are often observed at larger scales (e.g. recently Vaughan and Worthington, 2000). One case presented by Muschinski and Wode (1998) is a relative humidity increase of 25% within a 2-m interval and a wind shear of 160 $\mathrm{m\,s^{-1}km^{-1}}$. The conditions were dynamically unstable (the Richardson number $Ri < 1/4$ and the Reynolds number Re was large) but since no overturning was observed, the authors claimed that the sheet could be observed during the initial phase of Kelvin-Helmoltz instabilities. It is worth noting that Dalaudier et al. (1994) could not find characteristic structures in the relative wind velocity profiles within the vertical extent of the sheets. The absence of shear would indicate a different nature of the observed sheets. By using simple physical considerations, Muschinski and Wode (1998) calculated the life duration of the sheet and found up to 9.5 hours. This result is compatible with the long-lived echoing layers seen by ST radars. For this calculation, they considered only the effects of the molecular diffusion and not the turbulent diffusion that could be much more efficient for the destruction of the sheets. They also observed a turbulent layer as thin as 10 meters, which is in agreement with the observations of Barat (1982) of a turbulent layer of 20 meters in thickness in the velocity field of the lower stratosphere.

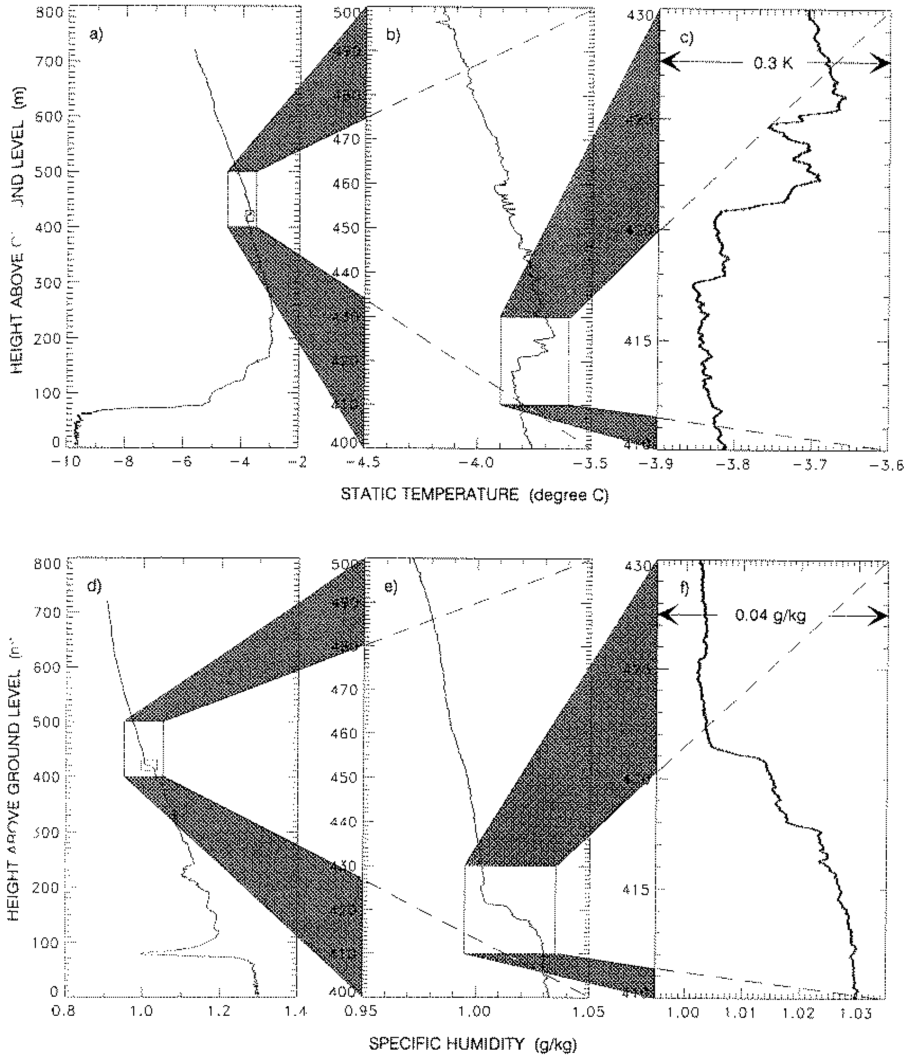

Fig. 15. Three successive close-ups of temperature **(a)–(c)** and humidity **(d)–(f)** profiles measured within the boundary layer with helicopter born high-resolution sensors indicating submeter sheets, e.g. at 417 and 426 m (after Muschinski and Wode, 1998).

The horizontal extent and lifetime of the sheets within the atmosphere and their surface roughness remain open questions. From the measurements during the ascent and descent of the balloons, shown by Dalaudier et al. (1994), the same structures are not found exactly at the same altitudes from measurements separated by several kilometers. However, it seems that the horizontal extent of the regions where groups of sheets are embedded can reach several kilometers.

As a result of ocean measurements with two temperature sensors separated horizontally by 50 meters, Woods and Wiley (1972) reported sheet and layer structures with a horizontal extent larger than the horizontal distance between the sensors. Dugan (1984) and Marmorino (1984) presented thin sheets a few meter thick with a horizontal extent that can be larger than several kilometers. Distortions over several meters with large horizontal scales were also reported (Fig. 16). However, we must be very cautious when applying results from the ocean to the atmosphere because air is much more compressible than water in which salinity also plays an important role. Furthermore, the free atmosphere is much more subject to breaking wave events which generate turbulence.

From these measurements in the ocean, it is difficult to deduce if meter-scale distortions were detected. Dugan's results are very similar to the conclusions reached by du Castel et al. (1966) using aircraft-borne refractometers. According to their observations, the distortions of the sheets within the planetary boundary layer are composed of primary and secondary structures. The primary and secondary irregularities have a characteristic height of several meters and several tens of meters on a horizontal extent of several tens of meters and several kilometers, respectively.

6 Discussion of the recent radar investigations in the light of temperature sheet observations

As discussed in Sect. 4, comparisons between direct measurements of temperature sheets within the lower atmosphere and vertical echo power profiles at VHF strongly indicate that these structures contribute significantly around the zenith (Dalaudier et al., 1994; Luce et al., 1995). In Luce et

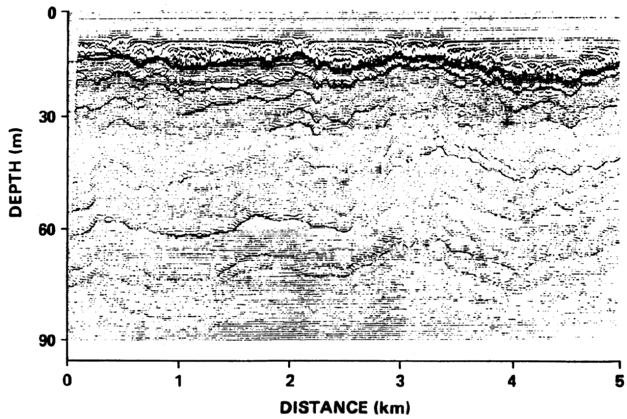

Fig. 16. Two-dimensional plot of vertical temperature gradient in the ocean from the surface to about 90 m using a towed vertical array of sensors separated by 50 cm. The dark regions correspond to high temperature gradients. They exhibit large horizontal scales (sometimes more than 1 km) and large-scale vertical displacements. It is difficult to obtain information on these displacements at a small-scale from this figure (after Dugan, 1984).

al. (1995), it was shown that the position of the selected sheets corresponds very well with the heights of the vertical echo power enhancement, especially in the lower stratosphere. This result is, by itself, not surprising since they contribute greatly to the hydrostatic stability of the atmosphere and then to N^4 and, as discussed in Sect. 3, it is known that the vertical echo power profiles are directly proportional to N^4 in a dry atmosphere. However, since these small vertical extent structures are responsible for the majority of the radar echoes, and since the horizontal distance between the radar and the balloon can reach a few kilometers, it can be concluded that the horizontal extent of the region favorable to the sheet formation, and maybe to the sheets themselves, is probably of the same order of magnitude, compatible with the observations of Dugan (1984) and du Castel et al. (1966). Moreover, as discussed by Röttger (1980b) and Luce et al. (1995), the horizontal extent of the sheets must cover at least the first Fresnel zone (i.e. a few hundred meters in the lower stratosphere) for their contribution to radar echoes to be dominant. Considering that they are advected by the winds, and since the persistence of the enhanced radar echoes can be very large, it is not unusual to find (at least apparent) horizontal extents of the order of a few hundred kilometers or even 1000 km, as reported by Kilburn et al. (1995).

Arguing that multiple sheets can be embedded within a range gate of a few hundred meters, Röttger and Larsen (1990) suggested that they act as almost discrete targets which may move with different velocities leading to the very narrow superimposed spikes in the Doppler spectra.

The roughness and/or corrugation of the sheet surface is undoubted. However, the sole in-situ measurements by balloons, for example, which give rise to a profile, and then to the 1D spectrum of the fluctuations with the Taylor (frozen field) hypothesis along the path of the sensors, are not sufficient for a complete description of the characteristics of the structures. Indirect information can be obtained by using the VHF radar measurements of aspect sensitivity, assuming that the specular reflection from the atmospheric sheets is the effective mechanism. Diffuse reflection from sheets corrugated by gravity waves has been considered by Tsuda et al. (1997a) by using a realistic spectrum of vertical wave-induced motions given by Van Zandt and Fritts (1989). One of the advantages of this model, as stressed by the authors, is that its parameters are more constrained than the models of anisotropic backscattering. The total energy E of the gravity wave spectrum per unit mass and the characteristic vertical wavenumber m^* are the two important parameters of their model that can be estimated (at least roughly) by experiments. E was estimated to be of the order of 10 $\mathrm{m^2/s^2}$ and $1/m^*$ was found to be of the order of 2 km (Fritts et al., 1988) in the troposphere. The model fitted the aspect sensitivity observations up to 6 degrees for tropospheric echoes. The observations at larger zenith angles were also, at least qualitatively, understood by taking into account the horizontal component of the gravity wave motions.

As indicated by Worthington et al. (1999a, b), the shape of the horizontal anisotropy of aspect sensitivity is strongly related to the direction of the wind shear and occurs even for wind shears as small as 10 $\mathrm{m\,s^{-1}km^{-1}}$. This result cannot be interpreted by turbulent eddies elongated along the preferred horizontal direction, as proposed by Balsley and Gage (1981) for explaining echo power enhancement with a period of 180 degrees. Rather, the recent investigations suggest that the horizontal anisotropy is also caused by specular reflections from corrugated sheets. Instead of a surface roughness with a uniform irregularity distribution, as assumed by Luce et al. (1995), the quasi-sinusoidal variations of the echo power with the azimuth indicate a very important contribution of a large-scale corrugation of the sheet surface. Indeed, Tsuda et al. (1997b) showed that the presence of a monochromatic gravity wave with a large horizontal wavelength (of the order of 10 km) is at least qualitatively sufficient for explaining the azimuthal echo power dependence also observed by Palmer et al. (1998b). However, such a large-scale corrugation is not sufficient for interpreting the skew on one side of the echo power map in the horizontal, as observed by Worthington et al. (1999a,b). More complicated models of corrugated surfaces producing an asymetric backscattering pattern should be used. These models may be based on directional surface spectra (function of the azimuth with a maximum along the wind shear direction) and take inspiration from those used for describing the sea surface. Indeed, it can be speculated that the shear increases the density of the facets oriented toward the antennas in the opposite direction of the shear. This would explain the skew in the horizontal echo power map. It is also worth noting that the presence of a small number of dominant facets is compatible with the quasi-deterministic's apparent displacements of the scattering center in the time series at very short time scales, as described by Röttger et al. (2000a).

The rapid variations and complex structures in echo power maps of VHF radar backscatter observed by Worthington et al. (2000a) and by Chau and Woodman (2001) with different imaging techniques may suggest that the tropospheric sheet surfaces are also characterized by high-frequency distortions, which affect the images at short time resolutions.

7 How are the temperature sheets generated?

Since the structures responsible for partial reflection of radio waves have been postulated and long before their existence, were confirmed within the atmosphere, the question of the mechanisms responsible for their generation has been investigated. This problem is also intimately related to their destruction or erosion mechanism. The balance between generation and destruction of such structures is responsible for the statistical characteristics of the VHF radar echoes. Furthermore, while the only available destruction mechanism is the diffusion (molecular or turbulent), it is extremely noteworthy that most of the proposed generation mechanisms are also based on the action of turbulent mixing.

However, some mechanisms are not direct consequences of turbulent mixing: the non-linear steepening of gravity waves can produce strong temperature gradients. The resulting sheets would evolve with the same period and propagate with the same speed as the wave. Gradients in the temperature field can also be produced by viscosity or thermal-conduction waves (Hooke and Jones, 1986; Hocking et al., 1991) which are almost non propagating (evanescent) solutions that can appear when internal gravity waves cannot propagate anymore (critical layer) and are partially reflected.

Another circumstance that could produce a strong temperature gradient is the initial stage of a Kelvin-Helmoltz billow development (e.g. Thorpe, 1987; Smyth and Moum, 2000). However, the strong gradient is necessarily associated with a strong mixing region which occurs nearby at the same altitude. Furthermore, it is not clear if the produced gradient survives the future development of the billow. In such a case, the K-H billow would be responsible for both the creation and destruction of the sheet.

Other proposed mechanisms rely on the irreversible modification of the temperature profile produced by turbulent mixing (homogeneization of the potential temperature). The main characteristic of such mechanisms is that the temperature sheet created at the "edge" of a turbulent patch can survive much longer than the patch itself (Coulman et al., 1995). In such a case, it is possible to observe temperature sheets which are not directly associated with turbulence.

Furthermore, once a patch of fluid has been mixed, the action of Archimede forces from the outside (non mixed) fluid, tends to crush it vertically, and can increase considerably its horizontal extent through "intrusion" of the mixed fluid in outer regions with similar potential temperature (Browand et al., 1987; Barenblatt, 1990). This vertical squeezing also increases the local temperature gradient.

The local (irreversible) evolution of the temperature gradient necessarily involves the (vertical) divergence of the heat flux. Two main mechanisms have been proposed to account for this divergence (Pelegri and Sangra, 1998). The first mechanism, which was proposed by Phillips (1972), basically argues that the heat flux is reduced in regions of stronger static stability, thus leading to an accumulation of heat above the forming sheet (and depletion of heat below), producing an instability and the growth of the gradient. Pelegri and Sangra (1998) emphasized difficulties with the Phillips mechanism and proposed an alternate scheme which relies primarily on the "memory" of turbulence (as pointed out by Barenblatt et al., 1993). Once the turbulence is created by a dynamical instability (a KHI for instance), it continues to mix the fluid and to reduce the local gradient, even if the instability conditions are no longer fullfilled.

8 Conclusions and perpectives

The presence and ubiquity of the temperature sheets in the free atmosphere are now undoubted (Dalaudier et al., 1994; Muschinski and Wode, 1998) and further similar balloon experiments confirmed this fact (Sidi and Dalaudier, internal communication). Using the theoretical developments proposed by Hocking and Hamza (1997), many recent studies on the origin of aspect sensitivity also indirectly point to the dominant contribution of atmospheric sheets to VHF radar echoes (e.g. Chen et al., 2000). Most of the aspect sensitive echoing layers seen by ST radars in vertical incidence and in standard or imaging modes are thus very likely produced by these very thin sheets at least in the lower stratosphere. Long before their existence was proved, diffuse scattering from their rough or corrugated temperature sheet surface was proposed in order to explain the zenithal angle dependence of echo power. The recent theoretical and experimental investigations of Tsuda et al. (1997a,b) and Worthingtion et al. (1999a,b), for example, gave extra credence to this hypothesis.

However, there are still many other open questions related to the temperature sheets. Their characteristics (e.g. horizontal extent, roughness or corrugation of their surface, life time, etc.) are presently poorly documented, especially in the lower stratosphere. A better knowledge of their characteristics is essential since it would permit us to determine more deeply the manner in which they contribute to the radar echoes at various beam directions and frequencies. Complementary radar Imaging techniques and colocated high-resolution in-situ measurements ought to give some new insights into the morphology of temperature sheets and their contribution to ST radar echoes. Two high-resolution balloon measurement campaigns are devoted to such studies within the troposphere and lower stratosphere. Firstly, the MUTSI (MU radar, Temperature Sheets and Interferometry) campaign was carried out in May 2000 and took place near the MU radar site (Shigaraki, Japan, 34.85° N, 136.10° E). This campaign resulted from a Franco-Japanese cooperation involving RASC (Japan), Service d'Aéronomie, LSEET, and Centre National d'Etudes Spatiales (CNES, France). It con-

Fig. 17. Capsphere balloons used during the MUTSI experiment (May 2000) near the MU radar.

sisted of launching small 'capsphere-type' balloons (Fig. 17) with instrumented gondolas including four high-resolution temperature sensors for measurement comparisons with MU radar data in different observational modes including spatial and frequency interferometries. More information on the MUTSI experiment can be found in Luce et al. (2000c).

Secondly, using their experience in the domain of high-resolution measurements with balloon born gondolas, Service d'Aéronomie is also currently preparing an original project called MUST2D (MicroSTructure 2 Dimensions). The experiment will consist of performing temperature measurements with 255 high-resolution sensors (as those used during MUTSI) vertically hung below a stratospheric balloon. The objective will be to collect bi-dimensional maps of the temperature field similar to those already presented by Dugan (1984) for the ocean. They intend to collect detailed information on the 2D temperature fluctuation spectra at small scales which are not accessible from classical radiosoundings with a single sensor. More information on the horizontal extent of the temperature sheets and turbulent layers and on the roughness of the sheet surface could also be obtained. Such detailed measurements could then be very useful in order to validate various hypotheses explaining radar aspect sensitivity at VHF.

Furthermore, recent investigations have been performed for simulating Doppler spectra of VHF radars. The development of numerical simulations could also offer strong potentials for radar and atmospheric physics, even if they are still limited by the hypotheses used. Muschinski et al. (1999) used the Large-Eddy Simulation (LES) technique with Kolmogorov-scaling arguments (the cells of the grid are much larger than the Bragg wavelength) for the simulations of Doppler spectra within the convective boundary layer. Gibson-Wilde et al. (2000) simulated VHF Doppler spectra in the mesosphere resulting from turbulence induced Kelvin-Helmholtz instabilities.

Recent radar observations at a very high-time resolution (≈ 0.1 s) in spatial and interferometric observational modes also revealed unexpected echo characteristics at such a resolution (Röttger et al., 2000a). The quasi-deterministic evolution of the scattering center within the radar gate during the observation time needs to be considered carefully since it is not compatible within the "traditional" hypotheses used for the scattering theory from random media.

The combination of these different studies could also contribute to the improvement of our knowledge on the relationship between temperature sheets, turbulence and waves. This problem is intimately related to their generation mechanisms. They are most likely multiple and should depend on the considered scales. For more efficiency, it is probable that efforts should be put forth to undertake numerical simulations and laboratory experiments which are complementary to in-situ and remote sensing observations. Another underlying problem is to determine if such stable structures can affect the structure and dynamics of the largest scales and the vertical transport of the minor components within the stable atmosphere.

Appendix A Main techniques used for aspect sensitivity measurements

A schematic diagram representing the techniques that permits the measurement of aspect sensitivity is given in Fig. A1.

A1 Doppler Beam Swinging technique

The basic technique consists of collecting data from different directions using the vertical beam and two or four oblique beams. This configuration is by far the most widely used since it results from the operational configuration needed for horizontal and vertical wind measurements and momentum fluxes. A large number of papers have been published; one can refer to Campistron et al. (1999) for the most recent paper using this technique.

A2 Beam Scanning technique

The Beam Scanning technique is an extension of the previous one to steering in multiple directions. A very large number of simultaneous beam directions is only possible with a radar system like the MU radar which can steer the beam pulse to pulse (Fukao et al., 1985a,b). For more conventional systems with non-distributed transmitters, a large number of directions would imply too great a lag between the measurements collected in the first direction and in the last direction. The most recent results were presented by Palmer et al. (1998a), Worthington et al. (1999a,b, 2000a) and Luce et al. (2000b) with the MU radar.

A3 Broad-beam technique

The Broad-beam method has been introduced by Woodman and Chu (1989) and Chu et al. (1990). It consists of transmitting with a broad radar beam (7.4 degrees with the Chung-Li radar) in order to estimate the aspect sensitivity function from the Doppler spectra. Indeed, by spectral selectivity, it is possible to obtain the anisotropic angular pattern from the Doppler spectrum for small zenith angles in the case where the mean wind velocity is uniform within the beam and the variance of the turbulent velocities is small compared to this mean wind velocity. This technique seems to give similar results to the Beam scanning technique but investigations have been limited to tropospheric studies, due to low sensitivity.

A4 Preset Multi-Beam Forming technique

The Preset Multi-Beam Forming technique has been proposed by Brun et al. (1984) and Saada (1997) with the 45 MHz Provence radar (Crochet, 1986). It consists of taking advantage of ambiguity lobes produced when the antennas are separated by several half-radar wavelengths. For instance, if the dipoles are separated by two wavelengths, one can obtain three main beams (one vertical and two oblique). Due to the Doppler sorting, it is then possible to estimate the echo power in the different directions if the gain in each of the beam directions is correctly taken into account. The advantage of this technique is that it can collect instantaneous data in different zenith directions for a given azimuth with a classical radar system of crossed colinear-coaxial antennas.

A5 Postset Beam Forming technique

In the Spaced Antenna technique, the Postset Beam steering PBS (Röttger and Ierkic, 1985) or the Post-Statistic Steering PSS (Küdeki and Woodman, 1990; Palmer et al. 1990a) is used for synthesizing beam directions by phasing the received signal itself (PBS) or the signal statistics (PSS). These techniques have the potentialities to study the aspect sensitivity but have been used primarily for wind velocity measurements (e.g. Larsen et al., 1991; Palmer et al., 1991, 1993). However, using the PBS technique, Van Baelen et al (1991) have calculated the contour map of echo power distribution (2D imaging) within the vertical beam as far as 1.8 degrees from the zenith.

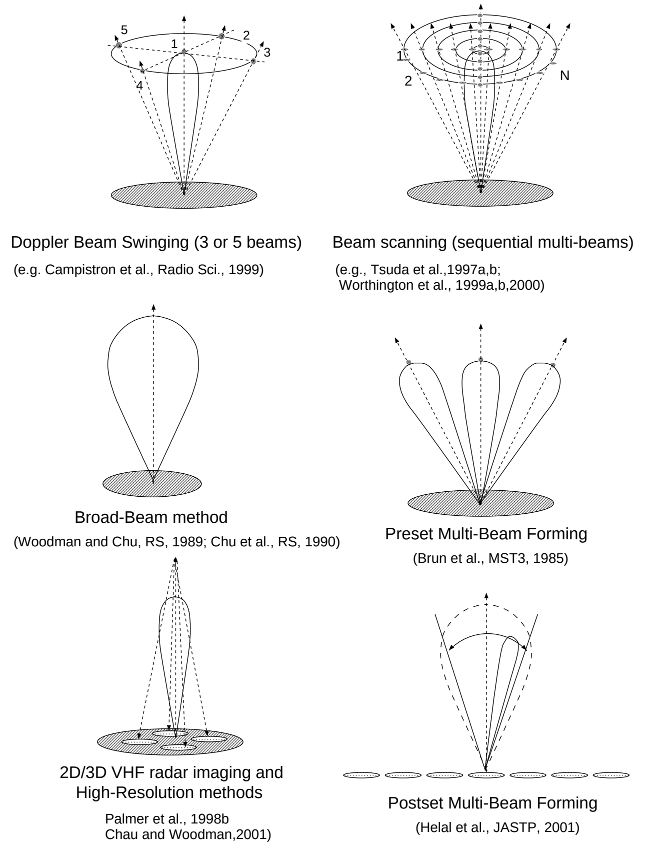

Fig. A1. Schematic representation of the different techniques that can be used for the study of aspect sensitivity.

A6 Radar Imaging techniques with High-Resolution methods

Recently, many investigations of the High-Resolution methods for imaging the radar returns have been carried out (see Chau, 2001 for details). Palmer et al. (1998a) used PSS with the Capon's Imaging (Capon, 1969) method, making use of optimization constraints for aspect sensitivity studies as far as 4 degrees from the zenith. The Capon's Imaging method exhibits a better resolving power than the Fourier-based Imaging which is a generalization of PSS. Chau and Woodman (2001) also performed coherent radar imaging using Capon's method and the Maximum Entropy method at mesospheric and tropospheric altitudes for aspect sensitivity studies within the radar lobe. Hélal et al. (2001) developed a Sequential PBS (SPBS) method for 2D or 3D imaging. It consists of collecting the data sequentially on each antenna by using fast switches and a single receiver in order to carry out angular scanning between -60 and +60 degrees with a cheap radar system. Capon's method was also applied as well as the Singular Value Decomposition method with the MUSIC algorithm (Bienvenu and Kopp, 1983). The SVD method has a better resolving power than Capon's method but cannot provide the reflectivity of the targets.

As long as VHF radars with very short pulses are not developed, the radar Imaging techniques are very promising for the study of the thin atmospheric layers and aspect sensitivity, and for the study of the nature of the structures that contribute to the radar echoes close to the zenith.

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